

# Constraining Dark Matter Properties with Gamma-Rays from the Galactic Center with *Fermi*-LAT

Nicolás Bernal<sup>1,2</sup> and Sergio Palomares-Ruiz<sup>2</sup>

<sup>1</sup>*Bethe Center for Theoretical Physics and Physikalisches Institut,  
Universität Bonn, Nußallee 12, D-53115 Bonn, Germany*

<sup>2</sup>*Centro de Física Teórica de Partículas (CFTP), Instituto Superior Técnico,  
Universidade Técnica de Lisboa, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal*

e-mails: nicolas@th.physik.uni-bonn.de, sergio.palomares.ruiz@ist.utl.pt

## Abstract

We study the capabilities of the *Fermi*-LAT instrument on board of the *Fermi* mission to constrain particle dark matter properties, as annihilation cross section, mass and branching ratio into dominant annihilation channels, with gamma-ray observations from the galactic center. Besides the prompt gamma-ray flux, we also take into account the contribution from the electrons/positrons produced in dark matter annihilations to the gamma-ray signal via inverse Compton scattering off the interstellar photon background, which turns out to be crucial in the case of dark matter annihilations into  $\mu^+\mu^-$  and  $e^+e^-$  pairs. We study the signal dependence on different parameters like the region of observation, the density profile, the assumptions for the dark matter model and the uncertainties in the propagation model. We also show the effect of the inclusion of a 20% systematic uncertainty in the gamma-ray background. If *Fermi*-LAT is able to distinguish a possible dark matter signal from the large gamma-ray background, we show that for dark matter masses below  $\sim 200$  GeV, *Fermi*-LAT will likely be able to determine dark matter properties with good accuracy.

**Keywords:** dark matter theory, gamma-ray theory, Milky Way

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# Contents

<b>1</b>	<b>Introduction</b>	<b>2</b>
<b>2</b>	<b>Gamma-Rays from the Galactic Center</b>	<b>3</b>
2.1	Prompt Gamma-Rays . . . . .	4
2.2	Gamma-Rays from Inverse Compton Scattering . . . . .	6
<b>3</b>	<b>Gamma-Ray Foregrounds</b>	<b>10</b>
3.1	Diffuse Galactic Emission . . . . .	11
3.2	Isotropic Gamma-Ray Background . . . . .	11
3.3	Point Sources . . . . .	11
<b>4</b>	<b><i>Fermi</i>-LAT sensitivity to DM annihilation</b>	<b>12</b>
<b>5</b>	<b>Constraining DM properties</b>	<b>15</b>
5.1	Dependence on the observational region . . . . .	18
5.2	Dependence on the DM density profile . . . . .	19
5.3	Dependence on systematic errors . . . . .	20
5.4	Dependence on the assumed DM model . . . . .	21
5.5	Dependence on the propagation model . . . . .	23
<b>6</b>	<b>Conclusions</b>	<b>24</b>
	<b>References</b>	<b>27</b>

# 1 Introduction

There exist compelling astrophysical and cosmological evidences that a large fraction of the matter in our Universe is non-luminous and non-baryonic (see Refs. [1–5] for reviews). These observations, and in particular the precise measurements from the Cosmic Microwave Background and Large Scale Structure, indicate that it constitutes  $\sim 80\%$  of the total mass content of the Universe [6, 7]. However, despite the precision of these measurements, the origin and most of the properties of the dark matter (DM) particle(s) remain a mystery; little is known about its mass, spin, couplings and its distribution at small scales. Nevertheless, DM plays a central role in current structure formation theories, and its microscopic properties have significant impact on the spatial distribution of mass, galaxies and clusters. Thus, unraveling the nature of DM is of critical importance both from the particle physics and from the astrophysical perspectives.

Many different particles have been proposed as DM candidates, spanning a very large range in masses, from light particles [8–17] to superheavy candidates at the Planck scale [18–26] (see, e.g., Refs. [4, 27] for a comprehensive list). Nevertheless, a weakly interacting massive particle (WIMP), with mass lying from the GeV to the TeV scale, is one of the most popular candidates for the DM of the Universe. WIMPs can arise in extensions of the Standard Model (SM) such as supersymmetry (e.g., Ref. [1]), little Higgs (e.g., Ref. [28]) or extra-dimensions models (e.g., Ref. [29]) and are usually thermally produced in the early Universe with an annihilation cross section (times relative velocity) of  $\langle\sigma v\rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ , which is the standard value that provides the observed DM relic density.

A variety of techniques has been considered to detect DM. Among these are collider experiments to produce DM particles or find evidence for the presence of particles beyond the SM, direct searches for signals of nuclear recoil of DM scattering off nuclei in direct detection experiments, and indirect searches looking for the products of DM annihilation (or decay), which include antimatter, neutrinos and photons. Once this is accomplished and DM has been detected, the next step would be to use the available information to constrain its properties. Different approaches have been proposed to determine the DM properties by using indirect or direct measurements or their combination [30–53]. In addition, the information that could be obtained from collider experiments would also be of fundamental importance to learn about the nature of DM [54–68] and could also be further constrained when combined with direct and indirect detection data [31, 62, 69–71].

In this work we study the abilities of the *Fermi*–LAT instrument on board of the *Fermi* mission to constrain DM properties, as annihilation cross section, mass and branching ratio into dominant annihilation channels, by using the current and future observations of gamma-rays from the Galactic Center (GC) produced by DM annihilations (see Refs. [72–76] for recent observations of high-energy gamma-rays from the GC by other experiments). In general, disentangling the potential DM signal from the background is the first task to be addressed. In addition to the usual approach of searching for spectral signatures above the expected background, *Fermi*–LAT can also make use of anisotropy studies and might be able to distinguish the spatial distribution of DM-induced gamma-ray signal from that of the conventional astrophysical background [77–92] (see also Refs. [93–95]). Throughout

this work we assume that a significant understanding of the large gamma-ray background will be achieved by *Fermi*–LAT.

Following Refs. [96,33] (see also Ref. [97]), our default squared region of observation covers a field of view of  $20^\circ \times 20^\circ$  around the GC (RA=266.46° and Dec=-28.97°, corresponding to the position of the brightest source, as in Ref. [98]) and, in order to model the relevant gamma-ray foregrounds we use *Fermi*–LAT observations. Both, for the simulations of the background and of the potential signal we use the *Fermi* Science Tools (version v9r23p1) [99]. As an improvement with respect to previous works [30–33], to the commonly considered gamma-ray prompt contribution, we add the contribution from the electrons and positrons produced in DM annihilations to the gamma-ray spectrum via inverse Compton scattering off the ambient photon background. This gamma-ray emission turns out to be not crucial in order to reconstruct DM properties for hadronic channels, but it is very important for DM annihilations into  $\mu^+\mu^-$  and  $e^+e^-$  pairs, providing completely wrong results if not included. As mentioned above, we do not include by default any uncertainty in the treatment of the background or the potential signal. Hence, in order to study the effect of different uncertainties and assumptions, we also show the results for two different observational regions, for two DM density profiles, for the case when systematical uncertainties in the gamma-ray background are taken into account (yet, in a simplified way), for different assumptions about the DM model and when uncertainties in the propagation model are also considered.

The paper is structured as follows. In Section 2 we describe the two main components of the gamma-ray emission from DM annihilations in the GC by reviewing the relevant formulae and commenting on the approximations we take. In Section 3 we describe the main gamma-ray foregrounds. We show the *Fermi*–LAT sensitivity to DM annihilation in Section 4 and present the *Fermi*–LAT prospects for constraining DM properties in Section 5, where we show the dependences on several uncertainties and assumptions. Finally, we draw our conclusions in Section 6.

## 2 Gamma–Rays from the Galactic Center

The differential intensity of the photon signal (photons per energy per time per area per solid angle) from a given observational region in the galactic halo ( $\Delta\Omega$ ) from the annihilation of DM particles has four main different possible origins: from internal bremsstrahlung and secondary photons (prompt), from Inverse Compton Scattering (ICS), from bremsstrahlung and from synchrotron emission, i.e.,

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega) = \left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\text{prompt}} + \left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\text{ICS}} + \left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\text{bremsstrahlung}} + \left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\text{synchrotron}}. \quad (1)$$

Bremsstrahlung is due to particle interaction in a medium and should not be confused with internal bremsstrahlung which is an electromagnetic radiative emission of an additional photon in the final state and is part of the prompt gamma-rays. For the energies of interest here and for the observational regions we consider, this contribution is expected to be subdominant with respect to ICS [100], so for the sake of simplicity we do not discuss it any further. On the other hand, synchrotron radiation arises from energetic electrons and positrons traversing the Galactic magnetic

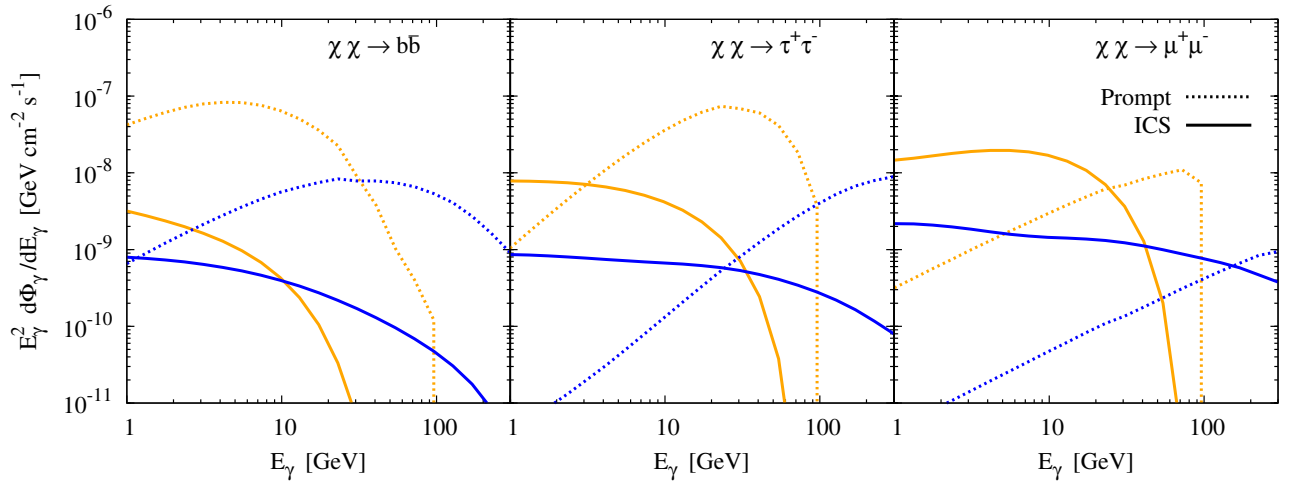


Figure 1: **Differential signal flux  $E_\gamma^2 d\Phi_\gamma/dE_\gamma$  in  $\text{GeV cm}^{-2} \text{s}^{-1}$  for the gamma-ray components** in the relevant energy range: prompt (dotted lines) and ICS (solid lines). We show the expected results for two different DM masses,  $m_\chi = 105 \text{ GeV}$  (light orange lines) and  $m_\chi = 1 \text{ TeV}$  (dark blue lines). Each panel depicts a DM particle that annihilates into:  $b\bar{b}$  (left panel),  $\tau^+\tau^-$  (middle panel) and  $\mu^+\mu^-$  (right panel). We assume a  $20^\circ \times 20^\circ$  observational region around the GC, a Navarro, Frenk and White DM halo profile, the MED model for the propagation model and  $\langle\sigma v\rangle = 3 \cdot 10^{-26} \text{ cm}^3 \text{s}^{-1}$ . See the text.

field. For typical WIMP DM masses, the DM-induced synchrotron signal lies at radio frequencies. However, these energies are well below the range of interest for an experiment as *Fermi*-LAT. Hence, we will also neglect this source of gamma rays in what follows. We note, however, that this contribution could also be used to constrain DM [101, 83, 102–107, 100, 108].

In Fig. 1, we depict the differential signal flux for  $\langle\sigma v\rangle = 3 \cdot 10^{-26} \text{ cm}^3 \text{s}^{-1}$ , for three different annihilation channels ( $b\bar{b}$ ,  $\tau^+\tau^-$  and  $\mu^+\mu^-$ ) and two different masses, 105 GeV (light orange lines) and 1 TeV (dark blue lines), in a  $20^\circ \times 20^\circ$  observational region around the GC with. We show the contribution to the signal from prompt (dotted lines) and ICS (solid lines) gamma-rays.

## 2.1 Prompt Gamma-Rays

Whenever DM annihilates into channels with charged particles in the final states, internal bremsstrahlung photons will unavoidably be produced. In addition to this, the hadronization, fragmentation, and subsequent decay of the SM particles in the final states will also contribute to the total yield of prompt gamma-rays.

The differential flux of prompt gamma-rays generated from DM annihilations in the smooth

DM halo <sup>1</sup> and coming from a direction within a solid angle  $\Delta\Omega$  can be written as [112]

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\text{prompt}}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_i \frac{dN_\gamma^i}{dE_\gamma} \text{BR}_i \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho(r(s, \Omega))^2 ds, \quad (2)$$

where the discrete sum is over all DM annihilation channels,  $dN_\gamma^i/dE_\gamma$  is the differential gamma-ray yield of SM particles into photons,  $\langle\sigma v\rangle$  is the thermal average of the total annihilation cross section times the relative velocity,  $m_\chi$  is the DM mass,  $\rho(r)$  is the DM density profile,  $r$  is the distance from the GC and  $\text{BR}_i$  is the branching ratio of DM annihilation into the  $i$ -th final state. We simulate the hadronization, fragmentation and decay of different final states with the event generator PYTHIA 6.4 [113], which automatically includes the so-called final state radiation (photons radiated off the external legs). The spatial integration of the square of the DM density profile is performed along the line of sight within the solid angle of observation  $\Delta\Omega$ . More precisely,  $r = \sqrt{R_\odot^2 - 2sR_\odot \cos\psi + s^2}$ , and the upper limit of integration is  $s_{\text{max}} = \sqrt{(R_{\text{MW}}^2 - \sin^2\psi R_\odot^2)} + R_\odot \cos\psi$ , where  $\psi$  is the angle between the direction of the galactic center and that of observation. As the contributions at large scales are negligible, different choices of the size of the Milky Way halo,  $R_{\text{MW}}$ , would not change the results in a significant way.

It is customary to rewrite Eq. (2) introducing the dimensionless quantity  $\bar{J}$ , which depends only on the DM distribution, as

$$\bar{J}(\Omega) = \frac{1}{\Delta\Omega} \frac{1}{R_\odot \rho_\odot^2} \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho(r(s, \Omega))^2 ds, \quad (3)$$

where  $R_\odot = 8.28$  kpc is the distance from the Sun to the GC and  $\rho_\odot = 0.389$  GeV/cm<sup>3</sup> is the local DM density [114]. The prompt gamma-ray flux can now be expressed as

$$\begin{aligned} \left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\text{prompt}}(E_\gamma, \Delta\Omega) &= 4.61 \cdot 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \left(\frac{100 \text{ GeV}}{m_\chi}\right)^2 \left(\frac{\langle\sigma v\rangle}{3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}}\right) \\ &\times \left(\frac{\bar{J}(\Delta\Omega)\Delta\Omega}{\text{sr}}\right) \sum_i \frac{dN_\gamma^i}{dE_\gamma} \text{BR}_i. \end{aligned} \quad (4)$$

The value of  $\bar{J}(\Delta\Omega)\Delta\Omega$  depends crucially on the DM distribution. Detailed structure formation simulations show that cold DM clusters hierarchically in halos and the formation of large scale structure in the Universe can be successfully reproduced. In the case of spherically symmetric matter density with isotropic velocity dispersion, the simulated DM profile in the galaxies can be parameterized via

$$\rho(r) = \rho_\odot \frac{[1 + (R_\odot/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}{(r/R_\odot)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}, \quad (5)$$

where  $r_s$  is the scale radius,  $\gamma$  is the inner cusp index,  $\beta$  is the slope as  $r \rightarrow \infty$  and  $\alpha$  determines the exact shape of the profile in regions around  $r_s$ .

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<sup>1</sup>Throughout this work we neglect the contribution due to substructure in the halo, which could increase the gamma-ray flux from DM annihilation by a factor of  $\sim 10$  [109–111].

	$\overline{J}(\Delta\Omega) \Delta\Omega$ [sr]	
	$20^\circ \times 20^\circ$	$2^\circ \times 2^\circ$
NFW	11.18	1.47
Einasto	19.92	2.25

Table 1: *Line of sight integrals of the square of the DM density profile.* Numerical values of  $\overline{J}(\Delta\Omega) \Delta\Omega$  for the NFW and Einasto DM density profiles for two observational regions around the GC:  $20^\circ \times 20^\circ$  and  $2^\circ \times 2^\circ$ .

There has been quite some controversy on the values for the  $(\alpha, \beta, \gamma)$  parameters. Commonly used profiles [115–119] (see also Refs. [120–124]) can differ considerably in the inner part of the galaxy giving rise to important differences in the final predictions for indirect signals from DM annihilation. Some N-body simulations suggested highly cusped inner regions for the galactic halo [117, 119], whereas others predicted shallower profiles [115, 116, 118]. The recent Via Lactea II simulations [110] seem to partly verify earlier results, the so-called Navarro, Frenk and White (NFW) profile [117] and find their results are well reproduced by  $(\alpha, \beta, \gamma) = (1, 3, 1)$  and  $r_s = 20$  kpc. On the other hand, the Aquarius project simulation results [111] seem to favor a different parameterization [125–128], which does not present this effect of cuspyness towards the center of the Galaxy, the so-called Einasto profile [129],

$$\rho(r) = 0.193 \rho_\odot \exp \left[ -\frac{2}{\alpha} \left( \left( \frac{r}{r_s} \right)^\alpha - 1 \right) \right], \quad \alpha = 0.17, \quad (6)$$

where  $r_s = 20$  kpc is a characteristic length. The values of  $\overline{J}(\Delta\Omega) \Delta\Omega$  for the two observational regions and for the two DM density profiles under discussion are given in Table 1.

## 2.2 Gamma–Rays from Inverse Compton Scattering

Energetic electrons and positrons produced in DM annihilations either directly or indirectly from the hadronization, fragmentation, and subsequent decay of the SM particles in the final states, give rise to secondary photons at various wavelengths via ICS off the ambient photon background (see Ref. [130] for a review). The differential flux  $d\Phi_\gamma/dE_\gamma$  of high energy photons produced by ICS, coming from an angular region of the sky denoted  $\Delta\Omega$ , is given by

$$\left( \frac{d\Phi_\gamma}{dE_\gamma} \right)_{\text{ICS}}(E_\gamma, \Delta\Omega) = \frac{1}{E_\gamma} \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{\text{los}} ds \int_{m_e}^{m_\chi} dE \mathcal{P}(E_\gamma, E) \frac{dn_e}{dE}(E, r_c(s, \Omega), z_c(s, \Omega)), \quad (7)$$

where the differential power emitted into scattered photons of energy  $E_\gamma$  by an electron with energy  $E$  is given by  $\mathcal{P}(E_\gamma, E)$  and  $dn_e/dE(E, r_c, z_c)$  is the number density of electrons and positrons with energy  $E$  at a position given by the cylindrical coordinates  $r_c$  and  $z_c$ , with its origin at the GC. The minimal and maximal energies of the electrons are determined by the electron mass  $m_e$  and

the DM particle mass  $m_\chi$ . The differential power is defined by

$$\mathcal{P}(E_\gamma, E) = \frac{3\sigma_T}{4\gamma^2} E_\gamma \int_{\frac{1}{4\gamma^2}}^1 dq \left[ 1 - \frac{1}{4q\gamma^2(1-\tilde{\epsilon})} \right] \frac{n_\gamma(\epsilon(q))}{q} \left[ 2q \ln(q) + q + 1 - 2q^2 + \frac{1}{2} \frac{\tilde{\epsilon}^2}{1-\tilde{\epsilon}} (1-q) \right], \quad (8)$$

where  $\sigma_T = 8\pi r_e^2/3 \simeq 0.6652$  barn is the total Thomson cross section in terms of the classical electron radius  $r_e$ ,  $\gamma = E/m_e \gg 1$  is the Lorentz factor of the electron (always assumed to be relativistic),  $\tilde{\epsilon} = \frac{E_\gamma}{\gamma m_e}$  and  $\epsilon(q) = \frac{m_e}{4\gamma} \frac{\tilde{\epsilon}}{q(1-\tilde{\epsilon})}$  is the energy of the original photon in the system of reference of the photon gas.

The ambient photon background in Eq. (8),  $n_\gamma(\epsilon)$ , consists of three main components: the cosmic microwave background (CMB), the starlight concentrated in the galactic plane (SL) and the infrared radiation due to rescattering of starlight by dust (IR). The spectrum of the interstellar radiation field (ISRF) in three dimensions over the whole Galaxy has been calculated in detail [131, 132]. However, for the sake of simplicity, in this work we will take an average density field for each of the regions of observation (but different for each region), instead of keeping the complete spatial dependence. Following Ref. [133], we approximate the total radiation density as a superposition of three blackbody-like spectra,

$$n_\gamma(\epsilon) = \frac{\epsilon^2}{\pi^2} \sum_{i=1}^3 \mathcal{N}_i \frac{1}{e^{\epsilon/T_i} - 1}, \quad (9)$$

with different temperatures and normalizations for each of the three contributions. In this work we study two squared regions of observation around the GC: our default region covers a field of view of  $20^\circ \times 20^\circ$ , but we also consider the case of  $2^\circ \times 2^\circ$ . Baring in mind that the observational region of  $20^\circ \times 20^\circ$  around the GC covers most of our default diffusive zone, we expect the modeling of the ISRF to approximately provide the correct results for the energy losses that enter in the diffusion-loss equation (see below). For instance, this occurs for the ISRF computed above the galactic plane at  $r_c = 0$  and  $z_c = 5$  kpc [131], which we use to parameterize this case. Note that although this position is not located within the region of observation, it provides very similar results to the ISRF at  $r_c = 8$  kpc and  $z_c = 0$  [131, 132]. On the other hand, for the  $2^\circ$ -side case, the average photon background density is expected to be larger, so we model this region with the computed ISRF on the galactic plane at a distance of 4 kpc from the GC [132]<sup>2</sup>. For the two regions of observation under study we use the modelization of the ISRF [131, 132] as given in Ref. [133]. The relevant parameters for the two observational regions are given in Table 2.

The quantity  $dn_e/dE$  in Eq. (7) is the electron plus positron spectrum after propagation in the Galaxy (number density per unit volume and energy), which will differ from the energy spectrum produced at the source. We determine this spectrum by solving the diffusion-loss equation that describes the evolution of the energy distribution for electrons and positrons assuming steady state [134]

$$\nabla \left( K(\vec{x}, E) \nabla \frac{dn_e}{dE}(\vec{x}, E) \right) + \frac{\partial}{\partial E} \left( b(\vec{x}, E) \frac{dn_e}{dE}(\vec{x}, E) \right) + Q(\vec{x}, E) = 0, \quad (10)$$

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<sup>2</sup>Note, however, that we use the same energy losses for all regions of observation as the electrons and positrons typically propagate within larger regions. Thus, to compute the effects of propagation, we always take the galactic average of the energy losses (see below).



	SL	IR	CMB
$T_i$	0.3 eV	3.5 meV	2.725 K
$\mathcal{N}_i(20^\circ \times 20^\circ)$	$8.9 \cdot 10^{-13}$	$1.3 \cdot 10^{-5}$	1
$\mathcal{N}_i(2^\circ \times 2^\circ)$	$2.7 \cdot 10^{-12}$	$7.0 \cdot 10^{-5}$	1

Table 2: *The parameters of the modelization of the ISRF taken from Ref. [133]. The  $20^\circ \times 20^\circ$  and  $2^\circ \times 2^\circ$  observational regions around the GC are modeled by the ISRF at  $(r_c, z_c) = (0, 5)$  kpc and  $(r_c, z_c) = (4, 0)$  kpc, respectively. See the text.*

where  $K(\vec{x}, E)$  is the space diffusion coefficient,  $b(\vec{x}, E)$  is the energy loss rate, and  $Q(\vec{x}, E)$  is the source term. The equation above neglects the effect of convection and reacceleration, which is in general a good approximation for the case of  $e^\pm$  [135].

The solution of the master equation, Eq. (10), without making any simplifying approximations, must be obtained numerically [136]. However, several assumptions allow for semi-analytical solutions of the problem which are able to reproduce the main features of full numerical approaches and are useful to systematically study the dependence on the various important parameters. Different approaches have been implemented in order to semi-analytically solve the diffusion equation, in the case that diffusion and energy losses do not depend on the spatial coordinates [137–141]. This is the approach we will follow.

The first term in Eq. (10) represents the diffusion of electrons and positrons and we take the diffusion coefficient as constant in space, and only depending on energy,  $K(E) = K_0 \beta (E/E_0)^\alpha$ , where  $K_0$  is the diffusion constant,  $\beta$  is the electron/positron velocity in units of the speed of light,  $\alpha$  is a constant slope,  $E$  is the  $e^\pm$  energy and  $E_0 = 1$  GeV is a reference energy.

On the other hand, the second term in Eq. (10) represents the energy losses. There are different processes that contribute to these losses: synchrotron radiation, bremsstrahlung, ionization and ICS. For electrons and positrons produced in DM annihilations in the Galaxy, the dominant processes are synchrotron radiation and ICS. In the Thomson limit,  $b(E) = E^2/(E_0 \tau_E)$ , where  $\tau_E = 10^{16}$  s is the characteristic averaged energy-loss time in the diffusive zone, i.e., energy losses are assumed to have no spatial dependence.

Finally, the source term due to DM annihilations in each point of the halo with DM density profile  $\rho(r_c, z_c)$  is given by

$$Q(r_c, z_c, E) = \frac{1}{2} \left( \frac{\rho(r_c, z_c)}{m_\chi} \right)^2 \langle \sigma v \rangle \sum_i \text{BR}_i \frac{dN_{e^\pm}^i}{dE}, \quad (11)$$

where  $dN_{e^\pm}^i/dE$  is the prompt electron plus positron spectrum produced in DM annihilations into channel  $i$ .

In this work we shall use the popular two-zone diffusion model and obtain the semi-analytical solution using the Bessel approach as described in detail in Ref. [141]. In this model, electron and positron propagation takes place in a cylindrical region (the diffusive zone) around the galactic center of half thickness  $L$  and radius  $R_{\text{gal}}$ ; the propagating particles being free to escape the region,

	$L$ [kpc]	$K_0$ [kpc <sup>2</sup> /Myr]	$\alpha$
MIN	1	0.00595	0.55
MED	4	0.0112	0.70
MAX	15	0.0765	0.46

Table 3: *Values of the propagation parameters that roughly provide minimal, median and maximal  $e^\pm$  fluxes compatible to the B/C data.*

a case in which they are simply lost. Regarding the propagation parameters  $L$ ,  $K_0$  and  $\alpha$ , we take their values from the commonly used MIN, MAX and MED models [141] (see Table 3), which correspond to the minimal, maximal and median primary positron fluxes over some energy range that are compatible with the B/C data [142]. However, it has been pointed out [141] that the propagation configurations selected by the B/C analysis do not play the same role for primary antiprotons and positrons. In particular, the MIN configuration for antiprotons [143] does not have an equivalent for positrons, for which it is not possible to single out one combination of the parameters which would lead to the minimal value of the positron signal. In any case, we consider these three (approximate) limiting models as a reference to set the uncertainty in the propagation parameters.

The resulting  $e^\pm$  flux from DM annihilations can be written as [137, 141]

$$\frac{dn_{e^\pm}}{dE}(r_c, z_c, E) = \frac{\beta \langle \sigma v \rangle}{2} \left( \frac{\rho(r_c, z_c)}{m_\chi} \right)^2 \frac{E_0 \tau_E}{E^2} \sum_i \text{BR}_i \int_E^{m_\chi} \frac{dN_{e^\pm}^i}{dE_s}(E_s) \tilde{I}(\lambda_D, r_c, z_c) dE_s, \quad (12)$$

where the final energy and that at the source are denoted by  $E$  and  $E_s$ , respectively. The so-called halo function,  $\tilde{I}(\lambda_D, r_c, z_c)$ , contains all the dependence on the astrophysical factors and is independent on the particle physics model. It is given by [141]

$$\tilde{I}(\lambda_D, r_c, z_c) = \sum_{i,n=1}^{\infty} J_0 \left( \frac{\alpha_i r_c}{R_{\text{gal}}} \right) \varphi_n(z_c) \exp \left[ - \left\{ \left( \frac{n\pi}{2L} \right)^2 + \frac{\alpha_i^2}{R_{\text{gal}}^2} \right\} \frac{\lambda_D^2}{4} \right] R_{i,n}(r_c, z_c), \quad (13)$$

where  $\lambda_D$  is the diffusion length, defined by

$$\lambda_D^2(E, E_s) = 4 K_0 \tau_E \left( \frac{(E/E_0)^{\alpha-1} - (E_s/E_0)^{\alpha-1}}{1 - \alpha} \right), \quad (14)$$

$\alpha_i$ 's are the zeros of the Bessel function  $J_0$  and  $\varphi_n(z_c) = (-1)^m \cos(n\pi z_c/(2L))$  with odd  $n = 2m + 1$ , which ensures that the halo function vanishes at the boundaries  $z_c = \pm L$ . The coefficients  $R_{i,n}$  are the Bessel and Fourier transforms of the DM density squared:

$$R_{i,n}(r_c, z_c) = \frac{2}{L R_{\text{gal}}^2} \frac{1}{J_1^2(\alpha_i)} \int_{-L}^{+L} dz \int_0^{R_{\text{gal}}} r dr \left[ \frac{\rho(r, z)}{\rho(r_c, z_c)} \right]^2 J_0 \left( \frac{\alpha_i r}{R_{\text{gal}}} \right) \varphi_n(z). \quad (15)$$

The advantage of this method is that (for each density profile and propagation model) the halo function  $\tilde{I}(\lambda_D, r_c, z_c)$  can be calculated and tabulated just once as a function of the diffusion length and the position, and then be easily used for performing parameter space scans which, as in our case, can be rather large.

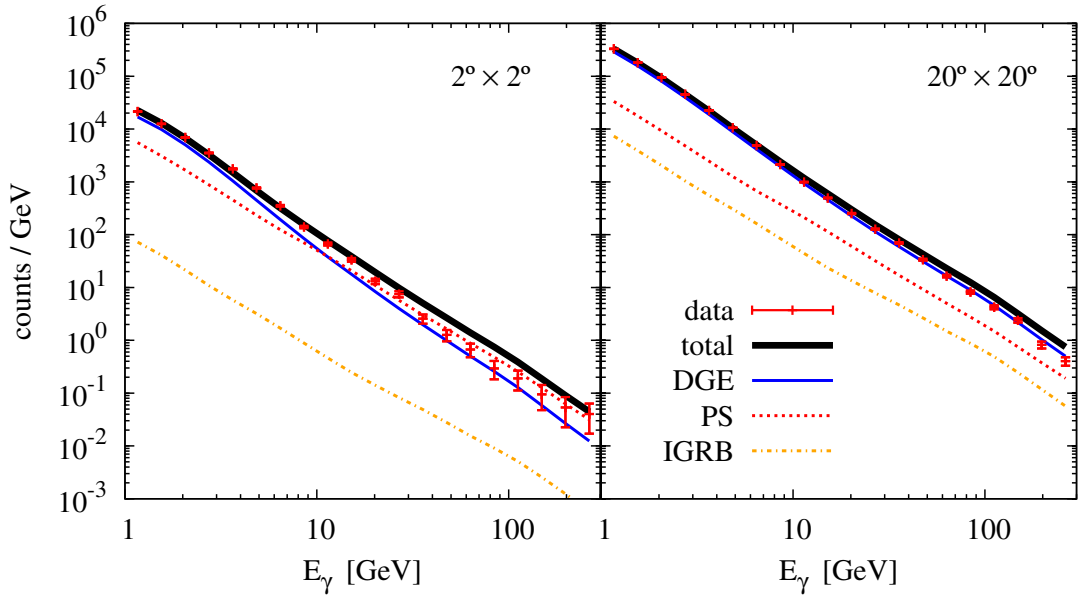


Figure 2: **Energy spectrum of the gamma-ray background.** The number of counts observed by *Fermi*–LAT from August 4, 2008 to July 12, 2011 are shown in red with error bars. The three components of the background obtained after performing an unbinned likelihood analysis of the data with the *Fermi* Science Tools (see text) are also depicted: diffuse galactic emission (thin solid blue line), isotropic gamma-ray background (dashed-dotted orange line), resolved point sources (dashed red line) and the total fitted contribution (thick solid black line). We show the results for two squared windows around the GC:  $2^\circ \times 2^\circ$  (left panel) and  $20^\circ \times 20^\circ$  (right panel).

### 3 Gamma-Ray Foregrounds

In Fig. 2 we show the *Fermi*–LAT data obtained from August 4, 2008 (15:43:37 UTC) to July 12, 2011 (09:45:27 UTC) in the two windows around the GC (RA=266.46° and Dec=−28.97°) considered here. We extract the data from the *Fermi* Science Support Center archive [144] and select only events classified as DIFFUSE, which are the appropriate ones to perform this analysis with the `gtselect` tool. We use a zenith angle cut of  $105^\circ$  to avoid contamination by the Earth’s albedo and the instrument response function P6V11. There are three components contributing to the high-energy gamma-ray background: the diffuse galactic emission (DGE), the isotropic gamma-ray background (IGRB) and the contribution from resolved point sources (PS). By making use of the public *Fermi* Science Tools (version v9r23p1) [99] we perform an unbinned likelihood analysis of the data with the `gtlike` tool and show these contributions. In the  $2^\circ \times 2^\circ$  region around the GC (left panel), the background coming from the resolved point sources is the dominant one for energies above  $\sim 10$  GeV. However, for a  $20^\circ \times 20^\circ$  region around the GC (right panel), the DGE is the most important one. The IGRB contribution, being at the percent level or smaller, does not have any effect on the results. Nevertheless, we have included it.

### 3.1 Diffuse Galactic Emission

The DGE is mainly produced by the interactions of cosmic ray nucleons and electrons with the interstellar gas, via the decay of neutral pions and bremsstrahlung, respectively, and by the inverse Compton scattering of cosmic ray electrons with the ISRF. We also note that the contribution from unresolved point sources is expected to be small [145] and is not taken into account here. Assuming that the cosmic ray spectra in the Galaxy can be normalized to the solar system measurements, the so-called conventional model was derived [136, 146, 147]. This model failed to reproduce the measurements by the EGRET experiment, in particular in the GeV range where the data shows an excess [148]. However, recent measurements by *Fermi*-LAT show no excess and are well reproduced by the conventional model, at least at intermediate galactic latitudes  $10^\circ < |b| < 20^\circ$  and up to 10 GeV [149, 150]. In order to model this foreground we use the *Fermi*-LAT model map `gll_iem_v02_P6_V11_DIFFUSE.fit` [151].

### 3.2 Isotropic Gamma-Ray Background

A much fainter and isotropic diffuse emission was first detected by the *SAS*-2 satellite [152] and later confirmed by the measurement reported by the EGRET experiment [153]. Although the term extragalactic gamma-ray background is commonly used, the extragalactic origin for this component is not clearly established [154–157], so we use the term isotropic gamma-ray background (IGRB). Among the possible contributions to this emission, we can list unresolved extragalactic sources such as blazars, active galactic nuclei, starbursts galaxies, star forming galaxies, galaxy clusters, clusters shocks and gamma-ray bursts [158–161] as well as other processes giving rise to truly diffuse emission [162, 163].

Recently the *Fermi*-LAT collaboration reported a new measurement of this high-energy gamma-ray emission [164], consistent with a power law with differential spectral index  $\alpha = 2.41 \pm 0.05$  and intensity  $\Phi(E_\gamma > 100 \text{ MeV}) = (1.03 \pm 0.17) \cdot 10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  [164], i.e., for the best-fit values,

$$\left( \frac{d\Phi}{dE_\gamma} \right)_{\text{IGRB}}(E_\gamma) = 5.65 \cdot 10^{-7} \cdot \left( \frac{E_\gamma}{\text{GeV}} \right)^{-2.41} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \quad (16)$$

Let us note, however, that this spectrum is significantly softer than the measured EGRET spectrum with index  $\alpha_{\text{EGRET}} = 2.13 \pm 0.03$  [153].

To simulate this background, we use the model map `isotropic_iem_v02_P6_V11_DIFFUSE.txt` supplied by the collaboration [151].

### 3.3 Point Sources

Finally, another important source of background particularly important when looking at the GC is that of resolved point sources. We consider the catalog of high-energy gamma-ray sources obtained by the first 11 months of *Fermi*-LAT (from August 2008 to July 2009). It contains 1451 sources detected with a significance better than  $4\sigma$  in the 100 MeV to 100 GeV range [165] and it represents a considerable increase with respect to the third EGRET catalog [166] which contained 271 sources.

All spectra have been fitted by power laws and we explicitly include all these sources in our analysis. Ideally, the total emission corresponds to a superposition of all the spectra within the region of observation

$$\left(\frac{d\Phi}{dE_\gamma}\right)_{\text{PS}}(E_\gamma, l, b) = \sum_{i \in \Delta\Omega} \phi_i \left(\frac{E_\gamma}{\text{GeV}}\right)^{-\alpha_i}. \quad (17)$$

However, due to the finite angular resolution of the experiment, in order to perform the fit, we have also included the contribution from point sources outside the region of observation. Note also that the *Fermi*–LAT catalog includes some sources which are found in regions with bright or possibly incorrectly modeled diffuse emission which could affect the measured properties of these sources, as well as sources with some inconsistency. Conservatively, we have also included these sources in our analysis.

## 4 *Fermi*–LAT sensitivity to DM annihilation

The *Fermi Gamma-ray Space Telescope* (*Fermi*) [167] was launched in June 2008 for a mission of 5 to 10 years. The Large Area Telescope (*Fermi*–LAT) is the primary instrument on board of the *Fermi* mission. It performs an all-sky survey, covering a large energy range for gamma-rays (from below 20 MeV to more than 300 GeV), with an energy and angle-dependent effective area which to good approximation is  $A_{\text{eff}} \simeq 8000 \text{ cm}^2$  and a field of view  $\text{FoV} = 2.4 \text{ sr}$ . Its equivalent Gaussian  $1\sigma$  energy resolution is  $\sim 10\%$  at energies above 1 GeV. In order to model the signal, we make use of the public *Fermi* Science Tools (version v9r23p1) [99], which allow us to properly simulate the performance of the experiment, taking into account the energy resolution, the point spread function, the dependence of the effective area with the energy, etc. In the following analysis, we consider a 5-year mission run, and an energy range from 1 GeV extending up to 300 GeV, divided with `gtbin` into 20 evenly spaced logarithmic bins. We generate photon events from DM annihilations according to the instrument response function by means of `gtobssim`.

On the other hand, the optimal size of the region of observation around the GC depends on different factors, from pure geometrical ones to the presence of the different type of foregrounds with different spatial dependences. It has been pointed out that in order to maximize the signal-to-noise ratio, the best strategy is to focus on a (squared) region around the GC with a  $\sim 10^\circ$  side for a NFW profile [96, 33]. Hence, we choose a squared region with a  $10^\circ$  side around the GC ( $20^\circ \times 20^\circ$ ) as our default region of observation. However, we will also illustrate some results for the case  $2^\circ \times 2^\circ$ .

By looking at the signal-to-noise ratio,  $S/N$ , where  $S$  is the signal and  $N = \sqrt{B}$ , with  $B$  being the background, one can also easily understand the relevance of the different components of the signal for each given set of the values of the parameters. We show the ratio  $S/N$  in Fig. 3 for three different annihilation channels ( $b\bar{b}$ ,  $\tau^+\tau^-$  and  $\mu^+\mu^-$ ) and two different masses (105 GeV and 1 TeV) after 5 years of data taking in a  $20^\circ \times 20^\circ$  region around the GC. We show the contribution to this ratio from prompt and ICS gamma-rays. As it is evident from the figure, for the case of DM annihilation into  $b\bar{b}$  (or more generically, into hadronic channels), the contribution from ICS gamma-rays is always subdominant with respect to that from prompt gamma-rays. This was

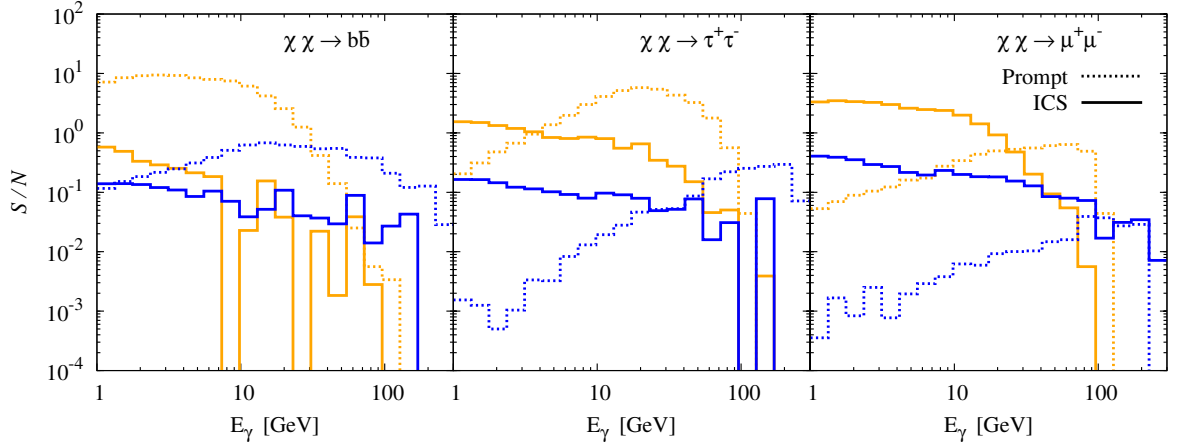


Figure 3: **The signal-to-noise ratio for all energy bins.** We show in each panel the case of two DM masses,  $m_\chi = 105$  GeV (light orange lines) and  $m_\chi = 1$  TeV (dark blue lines), and the individual results from the prompt (dotted lines) and ICS (solid lines) emission. The three panels correspond to DM annihilation into  $b\bar{b}$  (left panel),  $\tau^+\tau^-$  (middle panel) and  $\mu^+\mu^-$  (right panel). We assume 5 years of data taking with *Fermi*-LAT, a  $20^\circ \times 20^\circ$  observational region around the GC, a NFW DM halo profile, the MED model for the propagation model and  $\langle\sigma v\rangle = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ .

already apparent from Fig. 1. However, from Fig. 1 one would naïvely expect that for the case of DM annihilation into leptonic channels, the inclusion of the ICS contribution would have a very important effect in the results (the heavier the DM the more important), as the total yields come mainly from this component. Yet, this is not what Fig. 3 shows for the  $\tau^+\tau^-$  channel, whose ICS contribution is not as important as that from the  $\mu^+\mu^-$  (and, not shown here, the  $e^+e^-$ ) channel. This is easy to understand by recalling Figs. 1 and 2. For the energy window of observation and the parameters considered, the gamma-ray signal is dominated at low energies by ICS, but it is also at low energies where the background is higher. On the other hand, the background drops faster with energy than the signal, so even with fewer counts in the detector, the  $S/N$  ratio is larger at high energies where the prompt contribution is more important. The case of the  $\mu^+\mu^-$  (and  $e^+e^-$ ) channel is different in this regard; the prompt spectrum is harder than in the  $\tau^+\tau^-$  case and the yields are lower. As a consequence the ICS contribution dominates the signal up to much higher energies and hence its inclusion in the analysis renders necessary.

In order to evaluate the sensitivity of *Fermi*-LAT to DM annihilation we perform an analysis in terms of a  $\chi^2$  function, defined by <sup>3</sup>

$$\chi^2(m_\chi, \langle\sigma v\rangle) = \sum_{i=1}^{20} \frac{(S_i(m_\chi, \langle\sigma v\rangle))^2}{B_i}, \quad (18)$$

<sup>3</sup>In principle, this expression is only valid if, at least, there are several photons in each energy bin (the Gaussian limit). Although a priori this is not guaranteed, this is the actual situation for all the models above the sensitivity curves.

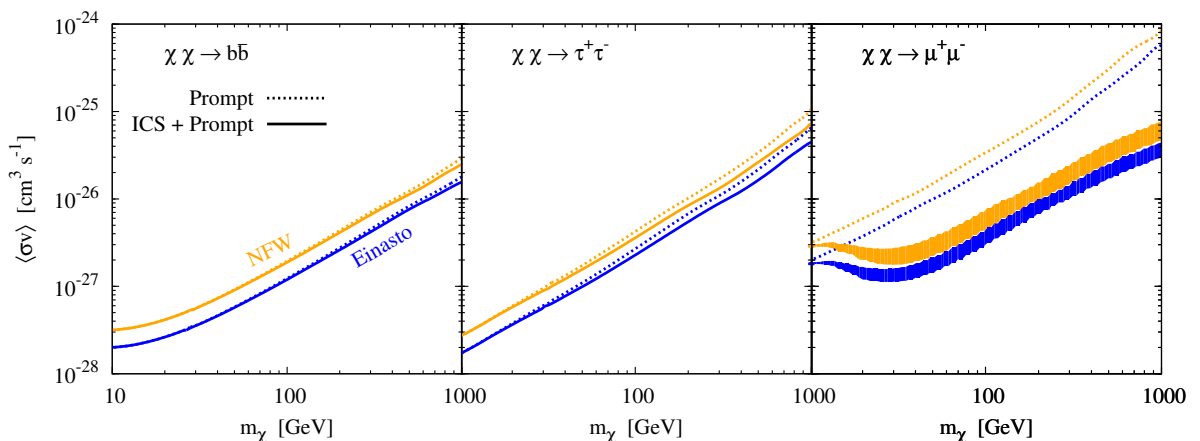


Figure 4: ***Fermi-LAT sensitivity.*** The regions on the parameter space  $(m_\chi, \langle\sigma v\rangle)$  that could be probed by the gamma ray measurements by *Fermi-LAT* after 5 years of data taking in a  $20^\circ \times 20^\circ$  observational region around the GC. The three panels correspond to DM annihilation into  $b\bar{b}$  (left panel),  $\tau^+\tau^-$  (middle panel) and  $\mu^+\mu^-$  (right panel). The solid (dotted) lines correspond to the 90% CL contours (1 dof) with (without) the ICS contribution and the light orange (dark blue) lines correspond to a NFW (Einasto) DM halo profile.

where  $S_i$  the number of signal (DM-induced) events in the  $i$ -th energy bin and  $B_i$  the corresponding background events in the same bin. Here we are assuming perfect knowledge of the background, but as mentioned in Ref. [168], an addition of a 20% uncertainty in the modeled background would only worsen the sensitivity by about 5%. However, let us note that the results presented here represent the most optimistic case. If the background is simultaneously fitted with the signal the results would worsen by an  $\mathcal{O}(1)$  factor.

In Fig. 4 we depict the sensitivity plots for a  $20^\circ \times 20^\circ$  observational region around the GC in the plane  $(m_\chi, \langle\sigma v\rangle)$  for the three annihilation modes:  $b\bar{b}$ ,  $\tau^+\tau^-$  and  $\mu^+\mu^-$ . The solid (dotted) lines correspond to the 90% confidence level (CL) for 1 degree of freedom (dof) contours with (without) the ICS contribution and the light orange (dark blue) lines correspond to a NFW (Einasto) DM halo profile. The solid bands represent the uncertainty in the propagation parameters, which are more important for the  $\mu^+\mu^-$  case for which the contribution from ICS clearly affects the results, improving the expectations of detection by an order of magnitude at high masses. Note however, that the uncertainty in the propagation parameters is smaller<sup>4</sup> than what would naïvely be expected from the differences in the halo function for the three propagation models (see e.g., Ref. [141]). Our findings agree with other related results, although obtained for a different observational region than the one considered in this study [169]. The regions above these lines represent the sets of parameters that could be probed by *Fermi-LAT* after 5 years of data taking. Notice that Ref. [168] (see also Ref. [30]) performed a similar analysis considering a region of  $0.5^\circ$  around the GC, which for a

<sup>4</sup>For a  $2^\circ \times 2^\circ$  observational region around the GC, these uncertainties are more important and make the bands slightly wider.

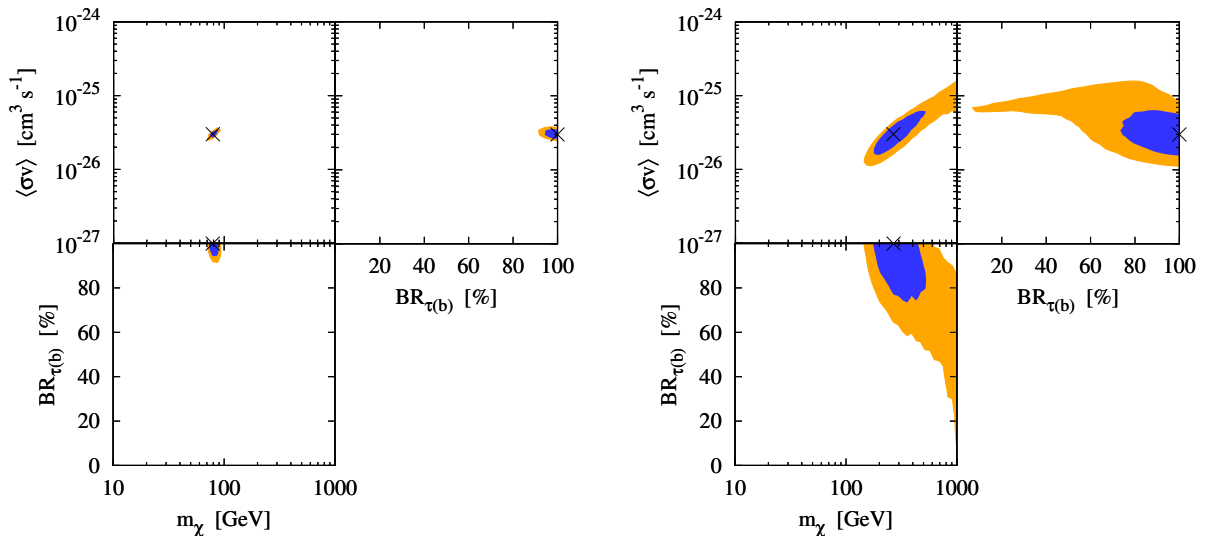


Figure 5: ***Fermi-LAT abilities to constrain DM properties.*** We consider DM annihilation into a pure  $\tau^+\tau^-$  final state and two DM masses:  $m_\chi^0 = 80$  GeV (left panels) and  $m_\chi^0 = 270$  GeV (right panels). Dark blue (light orange) regions represent 68% CL (90% CL) contours for 2 dof. We assume a  $20^\circ \times 20^\circ$  observational region around the GC, a NFW DM halo profile, the MED propagation model and  $\langle\sigma v\rangle^0 = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ . The parameters in this plot represent our default setup (see Table 4). The black crosses indicate the values of the parameters for the simulated observed “data”.

NFW density profile is expected to provide worse results by a factor of  $\sim 7-8$  [33, 96]. In addition to the different confidence level considered, there are also small differences with our assumptions in the binning, density profile parameters, etc. Finally, let us note that there is a minimum in the sensitivity curve when ICS is included in the  $\mu^+\mu^-$  case. This can be understood by the fact that below this mass, the signal-to-noise ratio due to the prompt signal starts to become comparable in the range of energies considered in this analysis (1 GeV–300 GeV) and thus, this curve tends to the case with only prompt gamma-rays.

As a general remark, the hadronic channels generate a higher yield of photons, giving rise to the most optimistic results. As already mentioned, in this case, the addition of the ICS contribution does not improve the results because it is always subdominant, even for large values of the DM mass (left panel of Fig. 4). On the other hand, the inclusion of the ICS contribution renders very important in the case of DM annihilations into the  $\mu^+\mu^-$  (and, not shown here, the  $e^+e^-$ ) channel.

## 5 Constraining DM properties

The analysis in the previous section showed the region in the parameter space for which DM could be distinguished from the background in the GC for different cases of DM annihilations into pure



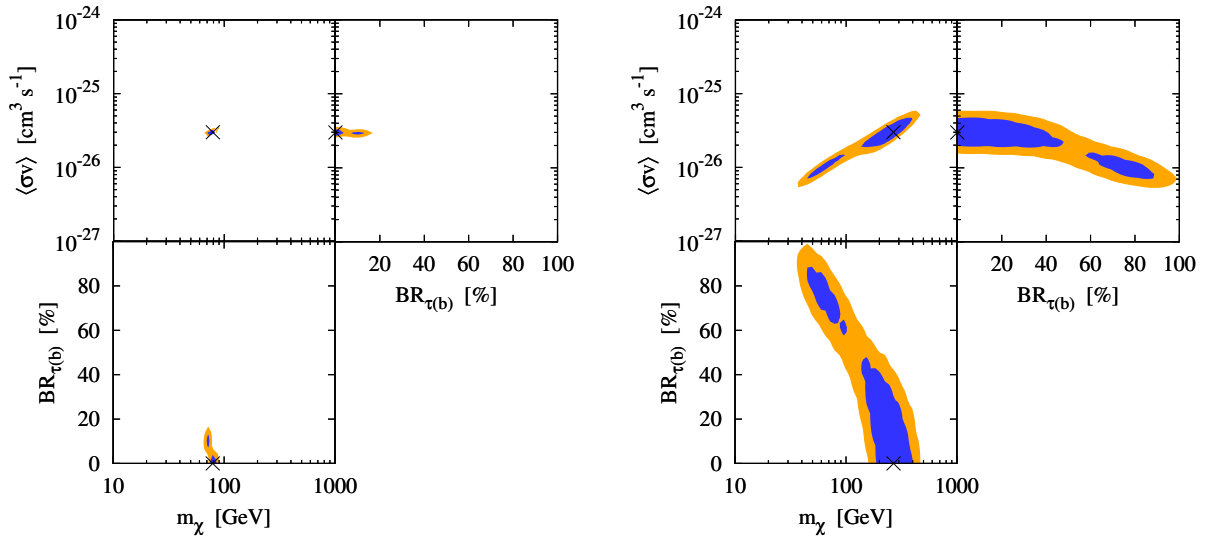


Figure 6: *Fermi-LAT abilities to constrain DM properties.* Same as Fig. 5 but for DM annihilations into a pure  $b\bar{b}$  final state.

channels<sup>5</sup>. Once this is accomplished, and gamma rays are identified as having been produced in DM annihilations, the next step concerns the possibilities of constraining DM properties. Different approaches have been proposed to constrain DM properties by using indirect searches, direct detection measurements, collider information or their combination [30–63, 65, 66, 64, 67–71]. These measurements are complementary and constitute an important step toward identifying the particle nature of DM. In this section we discuss *Fermi-LAT*’s abilities to constrain the DM mass, annihilation cross section and the annihilation channels after 5 years of data taking. In principle, the analysis should include all possible annihilation channels, but this would represent to have many free parameters. Nevertheless, in practice, they are commonly classified as hadronic and leptonic channels. Hence, for simplicity, when simulating a signal, we will only consider two possible (generic) channels. This reduces the number of total free parameters to three: the mass,  $m_\chi$ , the annihilation cross section,  $\langle\sigma v\rangle$ , and the branching ratio into channel 1,  $BR_{1(2)}$  (or equivalently into channel 2,  $BR_{2(1)} = 1 - BR_{1(2)}$ ). We use the  $\chi^2$  function defined as

$$\chi^2(m_\chi, \langle\sigma v\rangle, BR_{1(2)}) = \sum_{i=1}^{20} \frac{\left(S_i(m_\chi, \langle\sigma v\rangle, BR_{1(2)}) - S_i^{\text{th}}(m_\chi^0, \langle\sigma v\rangle^0, BR_{1(2)}^0)\right)^2}{S_i^{\text{th}}(m_\chi^0, \langle\sigma v\rangle^0, BR_{1(2)}^0) + B_i}, \quad (19)$$

where  $S_i$  represents the simulated signal events in the  $i$ -th energy bin for each set of the parameters and  $S_i^{\text{th}}$  the assumed observed signal events in that energy bin with parameters given by  $(m_\chi^0, \langle\sigma v\rangle^0, BR_{1(2)}^0)$ .

<sup>5</sup>This is not meant to represent realistic examples of DM candidates, but just to allow for a model-independent approach. For a particular particle physics model, one would expect that annihilations would occur into a combination of different channels, so our results should be taken as limiting cases of realistic models.

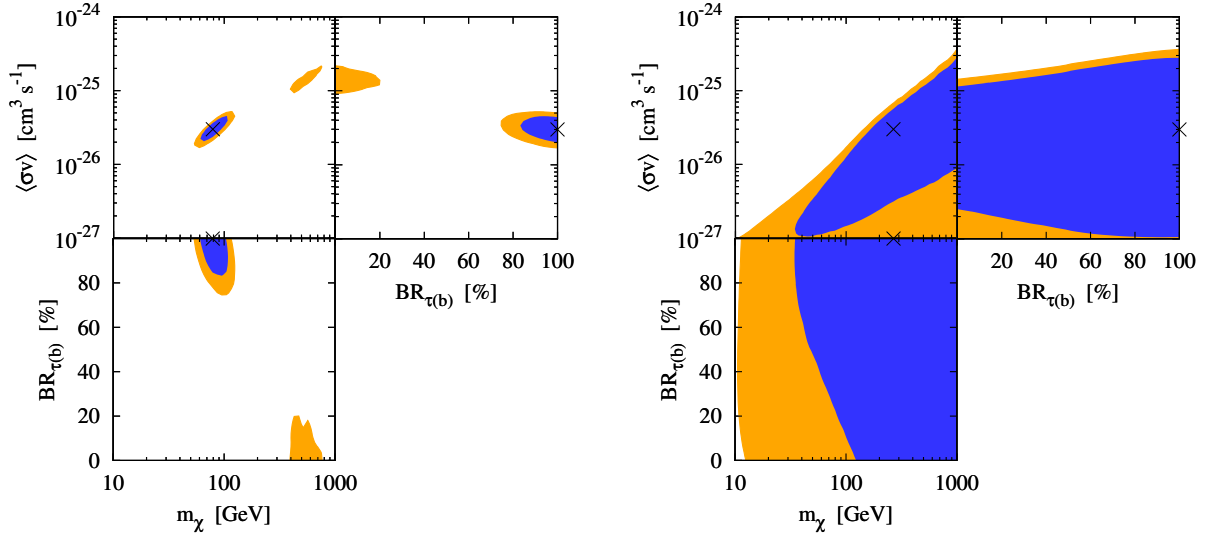


Figure 7: *Fermi-LAT abilities to constrain DM properties.* Same as Fig. 5 but for a  $2^\circ \times 2^\circ$  observational region around the GC.

For our default setup we consider a  $20^\circ \times 20^\circ$  (squared) observational region around the GC,  $\langle\sigma v\rangle^0 = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ , a NFW DM halo profile and the MED propagation model. Also by default, we consider annihilations into  $\tau^+\tau^-$  and  $b\bar{b}$ , both for the simulated observed “data” and the simulated signal. However, we will also consider the case of a simulated “data” with one channel and reconstructed signal with other two different channels and add the  $\mu^+\mu^-$  channel into the analysis. In Table 4 we summarize the parameters used in each of the figures we describe below.

In Fig. 5 we depict the *Fermi-LAT* reconstruction prospects after 5 years for our default setup (c.f. Table 4), i.e., DM annihilation into a pure  $\tau^+\tau^-$  final state reconstructed as a combination of  $\tau^+\tau^-$  and  $b\bar{b}$  and two possible DM masses:  $m_\chi^0 = 80 \text{ GeV}$  (left panels) and  $m_\chi^0 = 270 \text{ GeV}$  (right panels). By default, we also assume DM particle with an annihilation cross section  $\langle\sigma v\rangle = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ , the MED propagation model, a NFW DM halo profile and a  $20^\circ \times 20^\circ$  observational region around the GC. These benchmark points are represented in the figure by black crosses. The dark blue regions and the light orange regions correspond to the 68% CL and 90% CL contours (2 dof) respectively. In Fig. 5, the different panels show the results for the planes  $(m_\chi, \langle\sigma v\rangle)$ ,  $(\text{BR}_{\tau(b)}, \langle\sigma v\rangle)$  and  $(m_\chi, \text{BR}_{\tau(b)})$ , marginalizing with respect to the other parameter in each case. For the first model chosen in Fig. 5 (left panels),  $m_\chi^0 = 80 \text{ GeV}$ , the reconstruction prospects seem to be promising, allowing the determination of the mass, the annihilation cross section and the annihilation channel at the level of  $\sim 20\%$  or better. For lighter DM particles, the results substantially improve [33]. Thus, for this cases, after 5 years of data taking, *Fermi-LAT* could set very strong constraints on the properties of DM. On the other hand, for heavier DM particles, the regions allowed by data grow considerably worsening the abilities of the experiment to reconstruct DM properties. This is shown for the second model in Fig. 5 (right panels),  $m_\chi^0 = 270 \text{ GeV}$ . In this

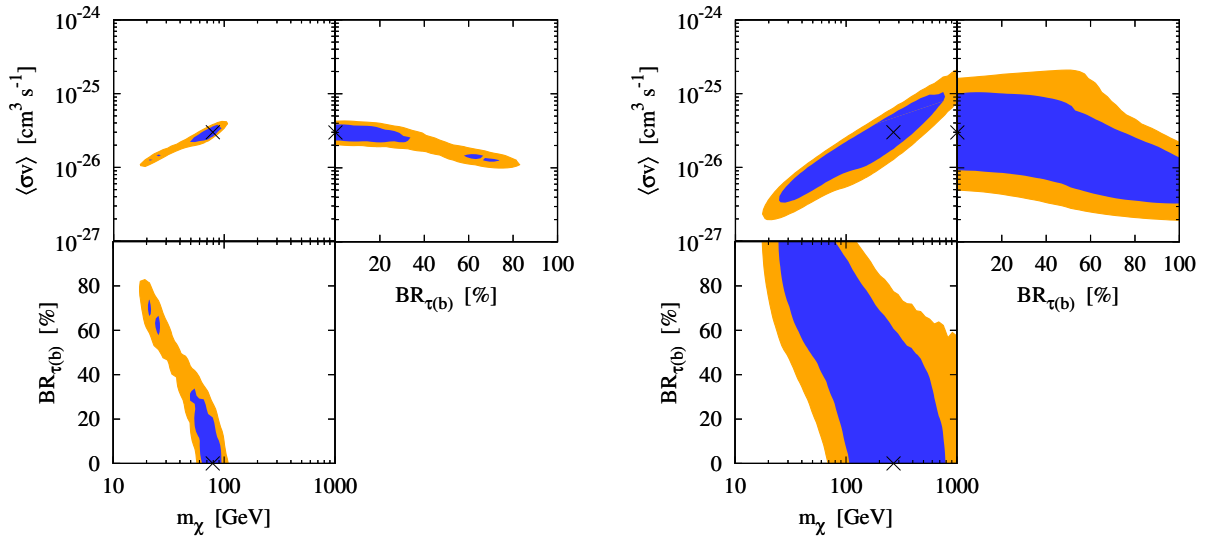


Figure 8: *Fermi-LAT abilities to constrain DM properties.* Same as Fig 6 but for a  $2^\circ \times 2^\circ$  observational region around the GC.

case, *Fermi-LAT* would only be able to set a lower limit (in the region of the parameter space we consider) on the DM mass ( $m_\chi \gtrsim 130$  GeV at 90% CL for 2 dof) and to constrain the annihilation cross section to be in the range  $9 \cdot 10^{-27} \lesssim \langle\sigma v\rangle \lesssim 2 \cdot 10^{-25} \text{ cm}^3 \text{s}^{-1}$  at 90% CL (2 dof). Moreover, only at 68% CL (2 dof) some limited information about the annihilation channel would be obtained.

On the other hand, Fig. 6 depicts the *Fermi-LAT* reconstruction abilities for a model similar to the one just discussed, but assuming DM annihilates into a pure  $b\bar{b}$  final state, instead of  $\tau^+\tau^-$ . As in the previous case, for light DM particles (left panels) the reconstruction prospects are very good. Note that the fact that the annihilation channel into  $b\bar{b}$  has a photon yield about an order of magnitude larger than the  $\tau^+\tau^-$  channel does not necessarily imply that DM properties could be better constrained in the  $b\bar{b}$  case. This can be understood by looking at Fig. 3, where we can see that the signal-to-noise ratio is similar for both cases. This is due both to the steep decrease of backgrounds with energy and to the fact that the gamma-ray spectrum in the  $\tau^+\tau^-$  case is harder and peaked close to the DM mass, so fewer statistics are necessary to get a reasonably good constrain on the DM mass. As can be seen from Fig. 6, in the  $b\bar{b}$  case, for  $m_\chi^0 = 270$  GeV (right panels) and at 90% CL (2 dof), *Fermi-LAT* would be able to constrain the DM mass to be in the range  $\sim(30\text{--}500)$  GeV and determine the annihilation cross section within an order of magnitude.

### 5.1 Dependence on the observational region

In Figs. 7 and 8 we show the results assuming the same properties for the DM particle as in Figs. 5 and 6, respectively, but assuming a  $2^\circ \times 2^\circ$  observational region around the GC, for which the background is dominated by resolved point sources. As can be seen from the figures, the prospects of constraining DM properties worsen in this case. This was already expected from the results

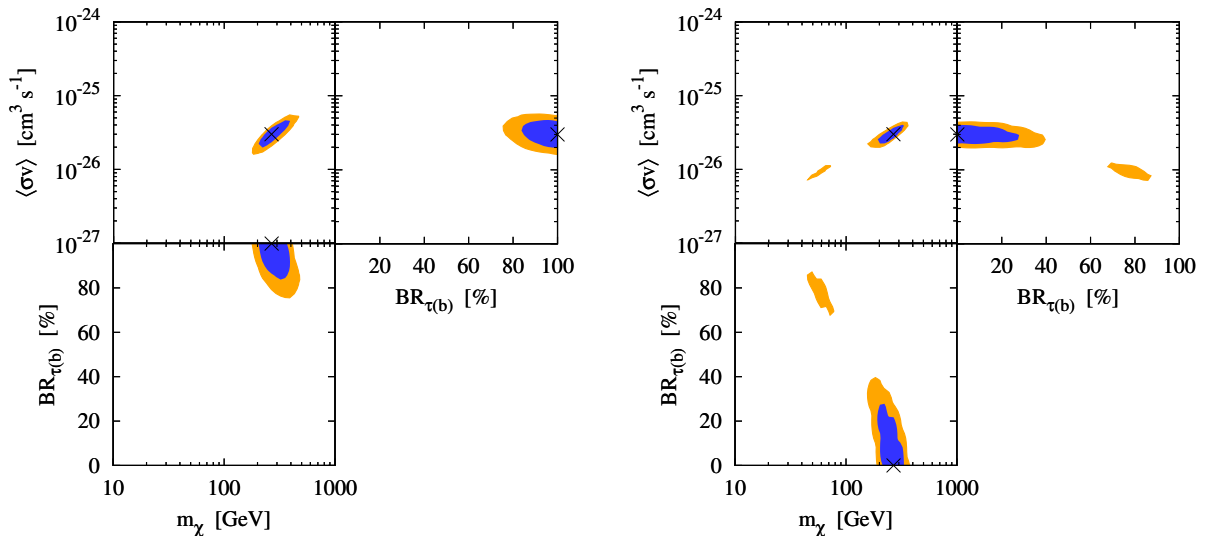


Figure 9: ***Fermi-LAT abilities to reconstruct DM properties for a Einasto DM halo profile.*** We assume  $m_\chi^0 = 270$  GeV and DM annihilation into  $\tau^+\tau^-$  (left panels) and  $b\bar{b}$  (right panels) final states. Dark blue (light orange) regions represent 68% CL (90% CL) contours for 2 dof. See Table 4 for the rest of the parameters. The black crosses indicate the values of the parameters for the simulated observed “data”.

in Refs. [96, 33]. In this case, second (spurious) minima appear at the 90% CL (2 dof) even for  $m_\chi = 80$  GeV at regions far from that of the simulated observed “data”. From Fig. 7 (left panels) we see that, assuming  $m_\chi^0 = 80$  GeV and annihilation into pure  $\tau^+\tau^-$  final state, there is a small region at 90% CL (2 dof) reconstructed with  $m_\chi \simeq 690$  GeV and annihilation into pure  $b\bar{b}$ . For  $m_\chi^0 = 270$  GeV, basically no information would be extracted, but just a very weak lower limit on the mass. Similar results are obtained for DM annihilation into  $b\bar{b}$  as can be seen from Fig. 8. In this case, the second minimum for the  $m_\chi = 80$  GeV case appear at lower masses and annihilation cross sections. For larger masses very restricted information would be available. Like in Figs. 5 and 6, the determination of the DM mass in this case is slightly worse than in the case of annihilation into  $\tau^+\tau^-$ , even with better statistics.

## 5.2 Dependence on the DM density profile

On the other hand, recent state-of-the-art N-body numerical simulations seem to converge towards a parameterization of the DM halo profile described by the Einasto profile (c.f. Eq. (6)) [125–128]. To illustrate this case, in Fig. 9 we show how the results would improve if the actual DM density profile is given by this parameterization. In this sense our previous results could be taken as a conservative approach. We depict the results for  $m_\chi^0 = 270$  GeV and for annihilations into pure  $\tau^+\tau^-$  (left panels) and  $b\bar{b}$  (right panels) final states. As in the previous figures, we take a typical thermal annihilation cross section,  $\langle\sigma v\rangle^0 = 3 \cdot 10^{-26}$  cm<sup>3</sup> s<sup>-1</sup>, the MED propagation model and a  $20^\circ \times 20^\circ$  observational

region around the GC. The left and right panels of this figure can be compared to the right panels in Figs. 5 and 6, respectively. Whereas in the case of a NFW profile only very limited information on the DM mass could be obtained at 90% CL (2 dof), if DM is distributed in the galaxy following a Einasto profile, the prospects would improve substantially. In the case of DM annihilation into a pure  $\tau^+\tau^-$  channel (left panels), the DM mass could be constrained with a  $\sim 50\%$  uncertainty and the annihilation into  $\tau^+\tau^-$  pairs with a branching ratio larger than 75% established. If DM annihilates into  $b\bar{b}$  pairs (right panels), except from a small region present only at 90% CL (2 dof), DM mass could also be determined with a  $\sim 50\%$  uncertainty and the annihilation branching ratio into the right channel would be constrained to be larger than 60%. As for the NFW case, in the Einasto case, for lighter DM candidates the abilities of *Fermi*-LAT would improve, whereas they would worsen if the DM particle is heavier.

Let us note that the profiles considered in this paper are obtained in DM-only simulations that do not include baryons. In principle, it is not yet clear how baryons would affect the profile of the Milky Way, but the picture could be significantly changed [170–180]. One possibility is adiabatic contraction [170], which would make the profiles steeper than in baryonless simulations, and thus we would expect a larger signal that would improve the detector sensitivity. However, we leave the discussion of how our results change due to the uncertainty on the DM density profile for future work [181].

### 5.3 Dependence on systematic errors

Now, let us discuss how our results are altered due to the uncertainties in the gamma-ray background we are considering. Here we only show the effects for the case of the  $20^\circ \times 20^\circ$  observational region around the GC, which is dominated by the DGE below  $\sim 20$  GeV. As an illustration, we only consider the error in the normalization of the total background, assigning a 20% uncertainty in its determination. The treatment of this systematic error is performed by the Lagrange multiplier method or also so-called pull approach [182–185]. We use a nuisance systematic parameter that describes the systematic error of the normalization of the background,  $\varepsilon_{\text{bkg}}$ , and the variation of  $\varepsilon_{\text{bkg}}$  in the fit is constrained by adding a quadratic penalty to the  $\chi^2$  function, which in the case of a Gaussian distributed error is given by  $(\varepsilon_{\text{bkg}}/\sigma_{\text{bkg}})^2$ , with  $\sigma_{\text{bkg}} = 0.2$  the standard deviation of the nuisance parameter  $\varepsilon_{\text{bkg}}$ . Hence, the simulated background events in each energy bin,  $B_i$ , are substituted by  $(1 + \varepsilon_{\text{bkg}}) B_i$  and Eq. (19) is modified as

$$\chi_{\text{pull}}^2 = \min_{\varepsilon_{\text{Bkg}}} \left\{ \sum_{i=1}^{20} \frac{(S_i + (1 + \varepsilon_{\text{bkg}}) B_i - S_i^{\text{th}} - B_i)^2}{S_i^{\text{th}} + B_i} + \left( \frac{\varepsilon_{\text{bkg}}}{\sigma_{\text{bkg}}} \right)^2 \right\}, \quad (20)$$

where  $\chi_{\text{pull}}^2$  is obtained after minimization with respect to the nuisance parameter  $\varepsilon_{\text{bkg}}$ .

The effects of adding this systematic error in the determination of the background are shown in Fig. 10. We show the results for DM annihilation into  $b\bar{b}$  final states with  $\langle\sigma v\rangle^0 = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ , assuming the MED propagation model, a NFW DM halo profile and a  $20^\circ \times 20^\circ$  observational region around the GC. For  $m_\chi^0 = 105$  GeV (left panels), the results do not change much, showing little effect due to this uncertainty in the background. However, for  $m_\chi^0 = 140$  GeV (right panels)

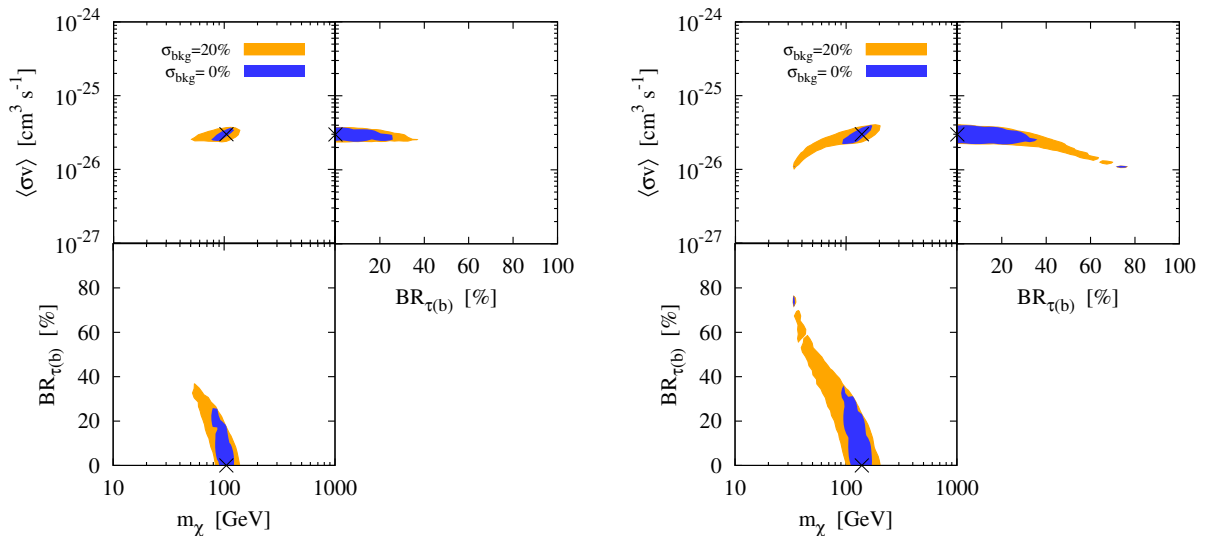


Figure 10: **Effects of adding a systematic error in the normalization of the gamma-ray background.** We assume DM annihilation into pure  $b\bar{b}$  final states and show the results at 90% CL (2 dof) for two DM masses:  $m_\chi^0 = 105$  GeV (left panels) and  $m_\chi^0 = 140$  GeV (right panels). Dark blue and light orange regions represent the case  $\sigma_{\text{bkg}} = 0$  (no error) and  $\sigma_{\text{bkg}} = 0.2$  in the gamma-ray background, respectively. See Table 4 for the rest of the parameters. The black crosses indicate the values of the parameters for the simulated observed “data”.

the second spurious minimum (c.f. right panels of Fig. 6) starts to show up when adding the error in the background normalization, worsening the results in a more significant way than for lighter masses. Nevertheless, when the second minimum is already present in the case of no error in the background (for slightly larger DM masses), taking into account this error in the background has a negligible effect. Thus, on general grounds, the error in the normalization of the measured gamma-ray background we have studied here would not substantially modify the results presented in this study regarding the abilities of *Fermi*-LAT to constrain DM properties. Let us however note that the actual systematic uncertainties in the modeling of the DGE are in principle larger than the considered 20% error, which could affect this analysis.

#### 5.4 Dependence on the assumed DM model

Throughout this work we have so far considered that DM would either annihilate into  $\tau^+\tau^-$  or  $b\bar{b}$  pairs or into a combination of them. This was in principle justified by the fact that DM annihilation channels are commonly classified into two broad classes: hadronic and leptonic channels. However, we noted in Section 4 that the contribution due to ICS in the case of the  $\mu^+\mu^-$  (and, not shown here, the  $e^+e^-$ ) channel could substantially alter the final sensitivity to DM annihilation from the GC. Thus, it is important to address the problem of assuming that DM actually annihilates into  $\mu^+\mu^-$  pairs, but we analyze the data assuming DM annihilations into  $\tau^+\tau^-$  and  $b\bar{b}$ . Naïvely, one would

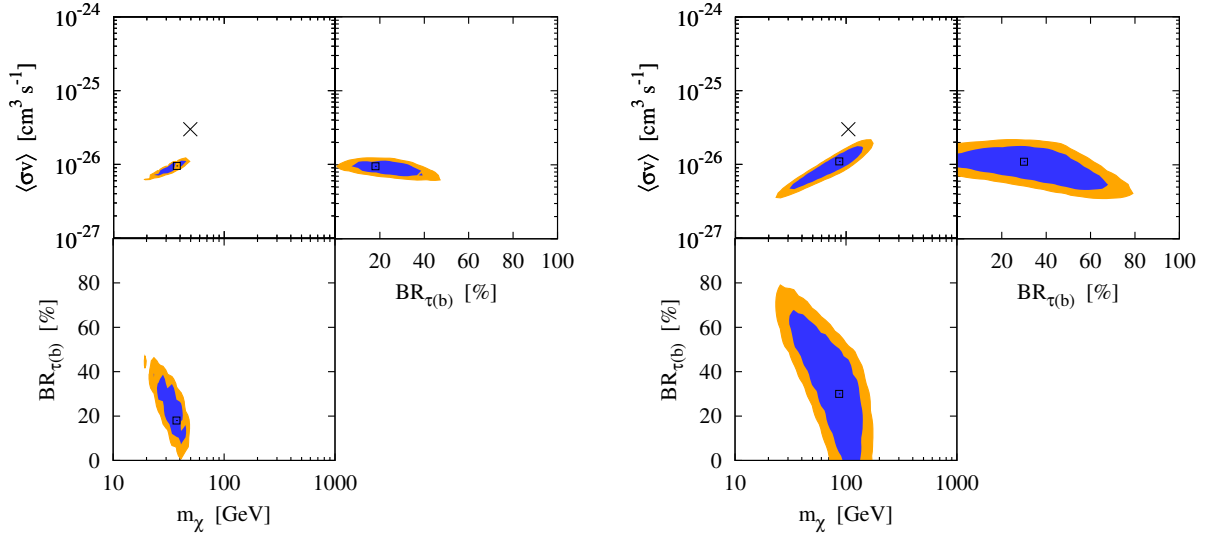


Figure 11: ***Fermi-LAT abilities to constrain DM properties.*** We assume the measured signal is due to DM annihilating into  $\mu^+\mu^-$ , but the fit is obtained assuming DM annihilates into a combination of  $\tau^+\tau^-$  and  $b\bar{b}$ . We assume two DM masses:  $m_\chi^0 = 50$  GeV (left panels) and  $m_\chi^0 = 105$  GeV (right panels). Dark blue (light orange) regions represent the 68% CL (90% CL) contours for 2 dof. See Table 4 for the rest of the parameters. The black cross in the left-top panel in each plot indicates the values of the parameters for the simulated observed “data”. Note that the other panels have no cross as they lie outside the parameter space of the simulated observed “data”. The squares indicate the best-fit point.

expect that the  $\mu^+\mu^-$  (leptonic) channel is identified as being closer to the  $\tau^+\tau^-$  (leptonic) channel than to the  $b\bar{b}$  (hadronic) channel. The results are shown in Fig. 11 for  $\langle\sigma v\rangle^0 = 3 \cdot 10^{-26}$  cm<sup>3</sup> s<sup>-1</sup>, the MED propagation model, a NFW DM halo profile, a  $20^\circ \times 20^\circ$  observational region around the GC and for two DM masses:  $m_\chi^0 = 50$  GeV (left panels) and  $m_\chi^0 = 105$  GeV (right panels). Contrary to what was expected, the reconstructed composition of the annihilation channels tends to be dominated by  $b\bar{b}$ , instead of  $\tau^+\tau^-$ . Hence, when taking into account the contribution of ICS to the gamma-ray spectrum, the annihilation channels cannot be generically classified as hadronic or leptonic, as DM annihilations into  $\mu^+\mu^-$  pairs are better reproduced with the  $b\bar{b}$  channels than with the  $\tau^+\tau^-$  channel.

The results just discussed can be illustrated in a different way by analyzing the simulated observed signal “data” from DM annihilation into  $\mu^+\mu^-$  assuming DM annihilates into  $\mu^+\mu^-$  and  $b\bar{b}$ . This is depicted in Fig. 12 where we show the results for the case that we try to reconstruct the signal adding the ICS contribution (left panels) or with only prompt photons (right panels). As can be seen in the left panels, if ICS is taken into account, DM properties can be reconstructed with good precision. However, if the ICS contribution is not added to the simulated signal events (the simulated observed “data” always has the ICS included), DM annihilation into a pure  $\mu^+\mu^-$  channel would be excluded at more 90% CL (2 dof), providing thus a completely wrong result.

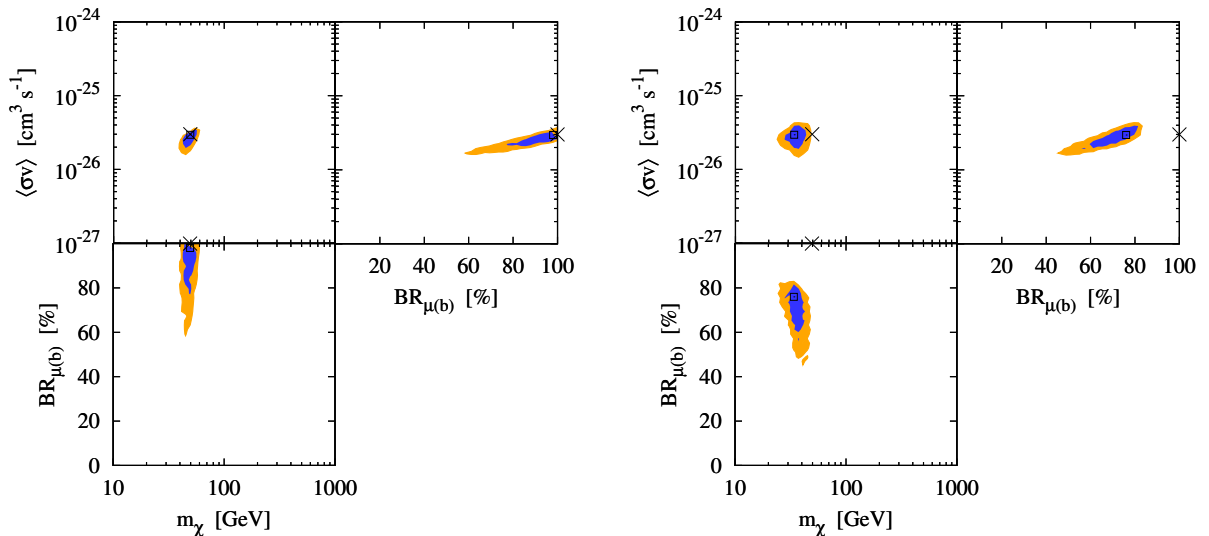


Figure 12: ***Fermi-LAT abilities to constrain DM properties.*** We assume the measured signal is due to DM annihilating into  $\mu^+\mu^-$  and the fit is obtained assuming DM annihilates into  $\mu^+\mu^-$  or  $b\bar{b}$ . We assume ICS+prompt photons (left panels) or only prompt photons (right panels) for the reconstructed signal, for  $m_\chi^0 = 50$  GeV. Dark blue (light orange) regions represent the 68% CL (90% CL) contours for 2 dof. See Table 4 for the rest of the parameters. The black crosses indicate the values of the parameters for the simulated observed “data”. The squares in the right panels indicate the best-fit point.

We conclude that, although the inclusion of the ICS contribution for hadronic channels and for the  $\tau^+\tau^-$  channel does not give rise to important differences in the presented results, this is not the case if DM annihilates into the  $\mu^+\mu^-$  (and, not shown here, the  $e^+e^-$ ) channel. In this latter case, adding the ICS contribution to the prompt gamma-ray spectrum renders crucial in order not to obtain completely wrong results.

## 5.5 Dependence on the propagation model

We have just seen that taking into account the contribution from ICS turns out to be fundamental if the DM signal is produced from DM annihilations into  $\mu^+\mu^-$  (and  $e^+e^-$ ). However, there are still a number of different uncertainties on the propagation of electrons and positrons in the Galaxy, which directly affect on the final ICS contribution to the DM-induced gamma-ray spectrum. Thus, the natural question to address is determining what the effect of these uncertainties is on the results presented here. In Fig. 13 we repeat Fig. 12, but in this case we take the MAX propagation model for the simulated observed “data” and the MIN propagation model for the simulated signal. Likewise, we constrain the signal adding the ICS contribution (left panels) or with only prompt photons (right panels). As can be seen by comparing both figures, the effect of adding the electron and positron propagation uncertainties does not alter significantly the conclusions reached with Fig. 12. Most



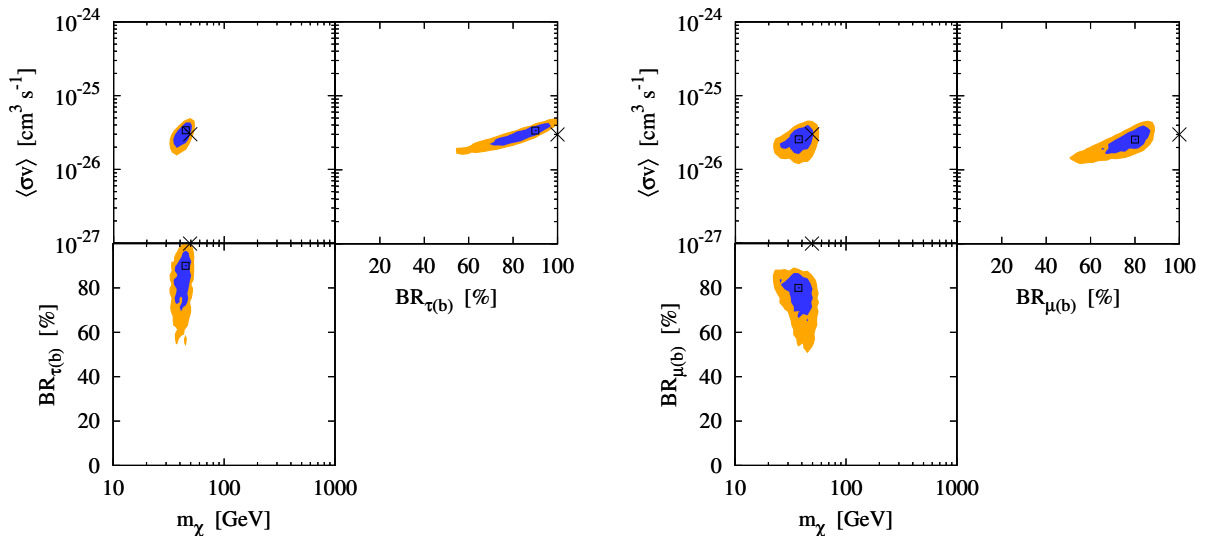


Figure 13: *Fermi-LAT abilities to constrain DM properties.* Same as Fig. 12, but assuming the MAX propagation model for the simulated observed “data” and the MIN propagation model for the simulated signal.

importantly, if the ICS component is not added to the simulated signal, DM annihilation only into the  $\mu^+\mu^-$  channel would also be excluded at much more than 90% CL (2 dof), and thus leading to misidentification of the nature of DM.

Finally, let us note that in this work we are using a simplified position-independent parameterization of the ISRF. A more detailed modelization would be required to compute more accurately the final ICS gamma-ray contribution to the potential signal and to fully take into account the effect of the induced uncertainties. However, the anisotropy of the background radiation field is not expected to induce corrections larger than  $\mathcal{O}(15\%)$  to the ICS contribution around the GC [186]. Another source of uncertainty comes from the fact that  $e^+e^-$  produced outside the diffusive zone can enter and get trapped in it and thus give rise to an increased ICS gamma-ray flux by  $\mathcal{O}(20\%)$  [187].

## 6 Conclusions

One of the most important topics in current astroparticle physics is the physics of DM. Its discovery and the determination of its nature once it is detected play a central role in astrophysics, cosmology and particle physics research. This is specially exciting in the light of recent data from direct detection experiments, which have further improved existing bounds and even hinted for a possible DM signal [188–191]. In addition to direct searches, there are other approaches that have been considered to detect DM: collider experiments could find evidences for the presence of particles beyond the SM which could be good DM candidates and indirect searches looking for the products of DM annihilation (or decay), as antimatter, neutrinos and photons. Indeed, also hints of a DM

signal have been recently suggested in indirect detection experiments [192–198].

Once DM has been detected and identified, the next step would be to use the available information from different experiments and constrain its properties. Different approaches have been proposed to determine DM properties by using future indirect DM-induced signals of gamma-rays or neutrinos, direct detection measurements, collider information or their combination [30–63, 65, 66, 64, 67–71].

In this work we have studied the abilities of the *Fermi*–LAT instrument on board of the *Fermi* mission to constrain DM properties by using the current and future observations of gamma-rays from the Galactic Center (GC) produced by DM annihilations. Unlike previous works [30–33], we also take into account the contribution to the gamma-ray spectrum from ICS of electrons and positrons produced in DM annihilations off the ambient photon background, which in the case of DM annihilations into  $\mu^+\mu^-$  and  $e^+e^-$  pairs turns out to be crucial.

After an introductory review of the main components of the gamma-ray emission from DM annihilations in the GC, where we explicitly write the relevant formulae, we discuss the three main gamma-ray foregrounds in the GC, which we obtain after performing an unbinned likelihood analysis (with the *Fermi* Science Tools) of the *Fermi*–LAT data collected from August 4, 2008 to July 12, 2011. We notice that for a  $2^\circ \times 2^\circ$  observational region around the GC, the high concentration of resolved point sources in the GC provides the dominant gamma-ray background above  $\sim 10$  GeV. However, for larger observational regions, as that with a field of view of  $20^\circ \times 20^\circ$  around the GC, the density of point sources dilutes and the dominant background is the DGE, primarily originated from the interaction of cosmic rays with the interstellar nuclei and the ISRF.

In Section 4 we describe the *Fermi*–LAT instrument on board of the *Fermi* mission, which we simulate by means of the tools provided by the collaborations. We first study the signal-to-noise ratio, Fig. 3, to understand the relevance of the different components of the signal. We see that, although in principle the inclusion of the ICS contribution is important for all leptonic channels, this does not seem to be the case for DM annihilations into the  $\tau^+\tau^-$  channel and in the energy range under study (1–300 GeV). Nevertheless, the ICS contribution is the most important one for the  $\mu^+\mu^-$  (and, not discussed here, the  $e^+e^-$ ) channel.

We then evaluate the *Fermi*–LAT sensitivity to DM annihilation in the GC after 5 years of data taking by observing a  $20^\circ \times 20^\circ$  region around the GC. We show the results in Fig. 4 for two different DM halo profiles, NFW and Einasto, and study the effect of the uncertainties in the propagation parameters, which turns out to be small in this observational region. We note that had we considered a smaller region of observation, these uncertainties would have had a more important effect. We see that for DM candidates lighter than 1 TeV annihilating into two SM particles, an overall conservative bound at 90% CL (1 dof) of  $\langle\sigma v\rangle < 10^{-25} \text{ cm}^3 \text{ s}^{-1}$  is obtained. The bound improves by more than two orders of magnitude for lighter DM particles and for annihilations into hadronic channels, being always below the benchmark value for thermal DM,  $\langle\sigma v\rangle^0 = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ , for all masses below 1 TeV and annihilations into  $b\bar{b}$  (or generically into hadronic channels).

In Section 5 we present the core results of our paper. We describe in detail the *Fermi*–LAT prospects for constraining DM properties for different DM scenarios. We also show the dependences

on several assumptions and how they may affect the abilities of the experiment to determine some DM properties, as DM annihilation cross section (times relative velocity), DM mass and branching ratio into dominant annihilation channels. Throughout the analysis, we have considered a default setup defined by a  $20^\circ \times 20^\circ$  observational region around the GC,  $\langle\sigma v\rangle^0 = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ , a NFW DM halo profile and the MED propagation model for electrons and positrons. Also by default, we have considered annihilations into  $\tau^+\tau^-$  and  $b\bar{b}$ , both for the simulated observed “data” and the simulated signal. We provide Table 4 where we summarize the different parameters used in each of the figures described in Section. 5.

Along the various figures in that section, we show the *Fermi*-LAT abilities to determine DM properties after 5 years of data taking, which is our default observation time. In Fig. 5 we show the reconstruction prospects for our default setup (DM annihilations into  $\tau^+\tau^-$ ). In Fig. 6 we just change the simulated observed “data” and assume that DM annihilates into  $b\bar{b}$ . With these figures we show the general trend of our results. For DM masses below  $\sim 200 \text{ GeV}$ , *Fermi*-LAT will likely be able to constrain the annihilation cross section, DM mass and dominant annihilation channels with good accuracy. The larger the DM mass, the more difficult this task will be, as the signal decreases with the DM mass.

Finally, we also study the effects of the dependence on different parameters, like the region of observation (Figs. 7 and 8), the DM density profile (Fig. 9), the particular assumptions for the DM model concerning annihilation channels (Figs. 11 and 12) and the uncertainties in the propagation model (Fig. 13). We also show the effect of the inclusion of a 20% systematic uncertainty in the gamma-ray background (Fig. 10). As mentioned above, one important result is that the commonly used classification of annihilation channels into hadronic or leptonic, based on the prompt gamma-ray spectrum, is not so clear when the ICS contribution is added. Indeed, DM annihilation into  $\mu^+\mu^-$  could be better fitted by DM annihilation into  $b\bar{b}$  than into  $\tau^+\tau^-$ . In addition, if the ICS contribution is not included in the simulated signals, one could reach wrong conclusions, as for instance incorrectly excluding DM annihilations into  $\mu^+\mu^-$  when the data is actually due to this annihilation channel. Hence, this is particularly important for any realistic model with significant dark matter annihilations into  $\mu^+\mu^-$  or  $e^+e^-$ , as for instance, any leptophilic DM models.

All in all, we would like to stress that the first task for any experiment aiming to detect DM is to distinguish it from any other possible source of signal or background. Here we have considered the GC, one of the most complex regions in the sky, which turns the modeling of the gamma-ray background into a difficult problem. In this context, multiwavelength studies will definitely be crucial to reduce all related uncertainties and reach a satisfactory understanding of the galactic foregrounds [101, 100, 199]. Baring carefully in mind these issues, our study shows the *Fermi*-LAT capabilities to constrain DM properties and can be used as a starting point for more detailed analysis, which will be needed when a convincing signal is detected, hopefully in the near future.

	$\theta_{\max}$	“Data”	Signal	$m_{\chi}^0$ [GeV]	DM Profile	$\sigma_{\text{bkg}}$	Prop. Model	$\langle\sigma v\rangle^0$ [cm <sup>3</sup> s <sup>-1</sup> ]
DS	20°	$\tau^+\tau^-$	$\tau^+\tau^-/b\bar{b}$	80/270	NFW	0	MED	$3 \cdot 10^{-26}$
Fig. 5	-	-	-	-	-	-	-	-
Fig. 6	-	$b\bar{b}$	-	-	-	-	-	-
Fig. 7	2°	-	-	-	-	-	-	-
Fig. 8	2°	$b\bar{b}$	-	-	-	-	-	-
Fig. 9	-	$\tau^+\tau^-/b\bar{b}$	-	270	Einasto	-	-	-
Fig. 10	-	$b\bar{b}$	-	105/140	-	0.2	-	-
Fig. 11	-	$\mu^+\mu^-$	-	50/105	-	-	-	-
Fig. 12	-	$\mu^+\mu^-$	$\mu^+\mu^-/b\bar{b}$	50	-	-	-	-
Fig. 13	-	$\mu^+\mu^-$	$\mu^+\mu^-/b\bar{b}$	50	-	-	MAX/MIN	-

Table 4: *Summary of the parameters used in each of the figures in Section 5.* The default setup is referred to as DS and  $\theta_{\max}$  indicates the size of the observational  $\theta_{\max} \times \theta_{\max}$  region around the GC. We indicate by ‘-’ when the parameters are the default ones. All the figures assume 5 years of data taking.

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